

# Optimal planning of battery energy storage considering reliability benefit and operation strategy in active distribution system



Wenxia LIU<sup>1</sup>, Shuya NIU<sup>1</sup>, Huiting XU<sup>1</sup>

**Abstract** In this paper, a cost-benefit analysis based optimal planning model of battery energy storage system (BESS) in active distribution system (ADS) is established considering a new BESS operation strategy. Reliability improvement benefit of BESS is considered and a numerical calculation method based on expectation is proposed for simple and convenient calculation of system reliability improvement with BESS in planning phase. Decision variables include both configuration variables and operation strategy control variables. In order to prevent the interaction between two types of variables and enhance global search ability, intelligent single particle optimizer (ISPO) is adopted to optimize this model. Case studies on a modified IEEE benchmark system verified the performance of the proposed operation strategy and optimal planning model of BESS.

**Keywords** Battery energy storage system, Cost-benefit analysis, Reliability improvement benefit, Operation strategy, Intelligent single particle optimizer

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## 1 Introduction

With development of new energy technology and support of governments, distributed generations (DGs) are paid widespread attention and adopted by more and more electric power users. In order to overcome negative impacts of DG integrating into grid, the concept of active distribution network was proposed by CIGRE C6.19 Working Group in 2008, which was subsequently changed into active distribution system (ADS) [1], aiming to actively control kinds of distributed energy resources (DERs), such as energy storage system (ESS), controllable load and DG, to achieve complementary and efficient operation. With characteristics of fast power adjustment and both supply and storage, ESS is important in ADS optimization operation [2]. And battery energy storage system (BESS) is widely applied because of high efficiency and adaptability to geographical conditions. Nowadays, advances in material science and power electronics technologies bring BESS into fast development. However, with high investment cost and short operation life of BESS, potential economic benefits for optimal configuration of BESS should be fully considered to promote investment for BESS and cost recovery.

The potentials of applying BESS into power systems contain improving voltage quality, reducing network loss, enhancing equipment utilization, and improving the penetration of intermittent DG in power grid [3, 4]. At present, there are two main research directions of BESS optimal planning in distribution network. The first one is to consider one or more potentials of BESS in distribution system to optimize size and/or location of BESS [5–8]. Taking sodium-sulfur battery as an example, BESS is modeled and simulated in [5], and results show that when allocated at reasonable node in distribution network with a rational



capacity, BESS can reduce line loss even considering heating loss of batteries. Capacity and power factor of BESS are optimized jointly in [6] to reduce loss of distribution network and improve voltage stability through coordination of BESS with photovoltaic (PV). A BESS capacity allocation method for improving PV penetration in distribution network is proposed in [7]. In [8], BESS capacity is addressed considering economic benefit of deferring network upgrade. The other research direction is determining optimal allocation of BESS by economic cost-benefit analysis in whole life cycle of BESS [9, 10], including benefits of decreasing grid expansion capacity, reducing total net loss cost by peak load shifting, arbitrage of energy storage, reducing capacity reserve for grid-connection of renewable energy resource, and cutting down BESS investment costs.

Most of the existing works have not taken into account the economic benefit of BESS in system failure status. As energy storage station, BESS can not only function in system normal operation but also supply electricity to important users as emergency power when system outage occurs, so as to reduce interruption duration and outage power and improve system reliability. Though reliability improvement benefit was also calculated in [9], with no consideration of grid structure would lead to inaccurate results. In this context, a numerical calculation method based on expectation is proposed which is suitable for simple and convenience calculation of system reliability improvement with BESS in planning phase. On the other hand, in most of previous works, BESS charging/discharging power of each hour in one day is taken as decision variable and carried out global optimization to obtain the optimal BESS operation strategy [9–11]. In order to reduce the computation scale, a new method for determining BESS operation strategy is proposed in this paper.

An optimal planning model of BESS is proposed in this paper to obtain the maximum economic benefit of BESS, under constraints of network security and meeting load demand. The rated power, capacity, location of BESS, and three operation strategy control variables are decision variables, and intelligent single particle optimizer (ISPO) is adopted to optimize this model. This paper can provide some guides for distribution company (DisCo) investing BESS in distribution network. The rest of the paper is organized as follows: Section 2 presents the procedure of BESS operation strategy determined by three decision variables. Section 3 describes calculation method of BESS reliability improvement benefit in two cases. BESS optimal planning model is formulated in Section 4. ISPO solving framework is shown in Section 5. Results and analysis are given in Section 6. Section 7 draws the conclusion.

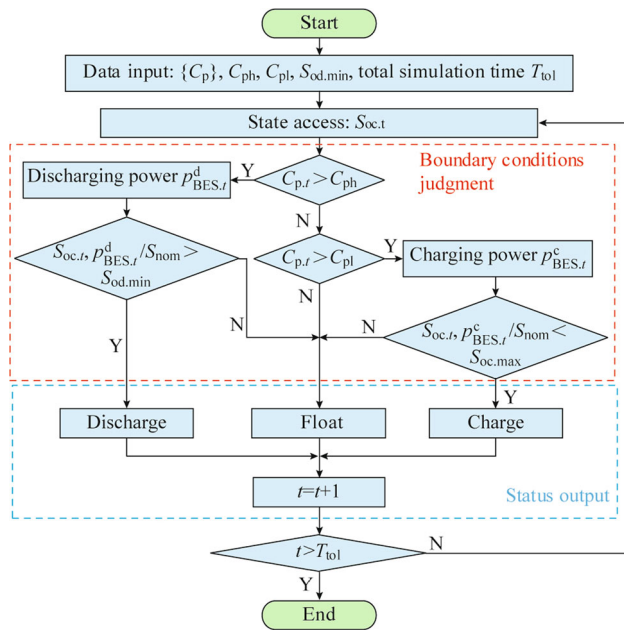
## 2 Operation strategy of BESS

Operation strategy of BESS refers to the power and time periods of battery charging and discharging [12]. In planning phase, BESS charging and discharging power of each period are usually taken as decision variables, globally optimized based on objective function. Compared to the fixed operation strategy, though this global optimization approach can obtain global optimal solution in theory, the dimension of programming model greatly increases and the computation speed is slow. On the other hand, in practical application, real-time control for BESS requires a lot of information exchanges and advanced communication equipment as supports, resulting in poor economy. Different from the approach of global optimization, some boundary values are set in this paper. When external conditions meet boundary constraints, BESS starts to charge or discharge, otherwise it goes into floating state. Moreover, in order to obtain the optimal solution, these boundary values cannot be fixed artificially beforehand but optimized in the simulation operation.

From the viewpoint of economy, electricity price of distribution system purchasing from upper system should be one of boundaries. The price lower limit for discharging and upper limit for charging are set as  $C_{ph}$  and  $C_{pl}$ , respectively. Furthermore, battery characteristic constraints should be considered in charging-discharging process. To ensure service life of batteries, state of charge (SOC) of BESS in any period should be in  $[S_{oc.min}, S_{oc.max}]$ .  $S_{oc.min}$  and  $S_{oc.max}$  represent the minimum and maximum SOC of BESS in physics.

In order to balance BESS benefits in normal operating state and in system failure state, the minimum permitting SOC of BESS ( $S_{od.min}$ ) is set in this paper which is different from  $S_{oc.min}$ . By setting  $S_{od.min}$ , remaining capacity of BESS in system normal operation can be always higher than a certain value, to guarantee BESS with enough energy to participate in system fault recovery. But if  $S_{od.min}$  is set too high, the benefit in normal operating state of BESS will be reduced. Thus  $S_{od.min}$  should also be optimized as a decision variable. The proposed BESS operation strategy is shown in Fig. 1, in which  $S_{nom}$  is the rated capacity of BESS.

To make full use of peak-valley difference of electricity price, charging and discharging power of BESS should vary with electricity price. When spot price  $C_{p,t}$  is higher than  $C_{ph}$ , the higher electricity price, the bigger discharging power is. Similarly, when spot price  $C_{p,t}$  is lower than  $C_{pl}$ , the lower electricity price, the bigger charging power is. Charging/discharging power of BESS in each period is expressed as:



**Fig. 1** Operation strategy of BESS

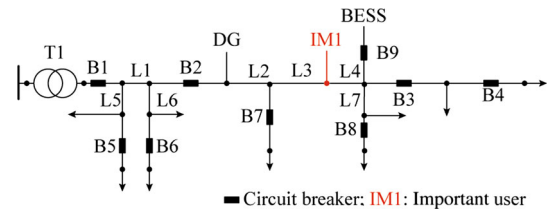
$$\begin{cases} p_{BES,t}^c = \frac{|C_{pl} - C_{p,t}|}{|C_{pl} - C_{p,min}|} P_{nom}, & \text{if } C_{p,t} < C_{pl} \\ p_{BES,t}^d = \frac{|C_{p,t} - C_{ph}|}{|C_{p,max} - C_{ph}|} P_{nom}, & \text{if } C_{p,t} > C_{ph} \end{cases} \quad (1)$$

where  $p_{BES,t}^c$ ,  $p_{BES,t}^d$  are charging power and discharging power of BESS at time  $t$ ;  $P_{nom}$  the rated power of BESS; and  $C_{p,max}$ ,  $C_{p,min}$  the maximum and minimum values of electricity price, respectively.

### 3 Reliability improvement benefit of BESS

In previous works, to assess the reliability of distribution system with BESS, a sequential Monte Carlo simulation method must be applied, whose process is complex and computation time is long, such as in [13]. A numerical calculation method based on expectation is proposed in this paper suitable for calculation of system reliability improvement with BESS in planning phase.

In Fig. 2, when B1 fails, DG, BESS and important user are in the same island. Important user is supplied by DG first and when DG output is insufficient, BESS continues to supply power to important user. Therefore, in this case, reliability improvement benefit of BESS is decided by the relationship between DG output and remaining capacity of BESS ( $S_{res}$ ) when fault occurs. When L2 fails, only BESS and important user are in the same island. In this case, reliability improvement benefit is just decided by  $S_{res}$  of BESS.  $S_{res}$  is related to the operation strategy of BESS in



**Fig. 2** Diagram of a feeder in distribution network

system normal status and proportional to  $S_{od,min}$ . Based on the above analysis, reliability improvement benefit of BESS is calculated in two cases.

#### Case 1: Only BESS and important users are in the same island

Annual reliability improvement benefit of BESS in Case 1 is

$$B_{relI} = \sum_{j=1}^I [\min(E_{ENS,j}, S_{res} - S_{min}) p_{BIO,j} R_{IEA,j}] \quad (2)$$

where  $I$  is the number of important users in distribution system;  $E_{ENS,j}$  the annual expected demand not supplied of important user  $j$ ;  $S_{res}$  the expected remaining energy of BESS when system failure occurs;  $p_{BIO,j}$  the probability of only important user  $j$  and BESS in the same island;  $R_{IEA,j}$  the outage evaluation rate of important user  $j$  (¥/kWh) and  $S_{min}$  the minimum capacity of BESS in physics, which is calculated as

$$S_{min} = S_{oc,min} S_{nom} \quad (3)$$

$E_{ENS,j}$  is related to electricity required for important user  $j$  and system grid structure.

$$E_{ENS,j} = \sum_{k=1}^{n_j} \lambda_k r_k \cdot p_{r,j} \quad (4)$$

where  $n_j$  is the set of elements whose fault can cause outage of important user  $j$ ;  $\lambda_k$ ,  $r_k$  the failure rate and average fault duration of element  $k$ , respectively; and  $p_{r,j}$  the power required for important user  $j$ .

$S_{res}$  can be calculated by SOC sequences which obtained by the BESS operation simulation.

$$S_{res} = \sum_{t=1}^T S_{oc,t} \frac{S_{nom}}{T} \quad (5)$$

where  $S_{oc,t}$  is SOC value of BESS at period  $t$ ;  $T$  the number of total research periods which is 8760 in this paper.

$p_{BIO,j}$  is related to the relative position between important user  $j$  and BESS in system.

$$p_{BIO,j} = p_{BI,j} - p_{DBI,j} \quad (6)$$

subject to



$$\begin{cases} p_{BI,j} = \frac{\sum_{i=1}^{n_{BI}} \lambda_i r_i}{\sum_{i=1}^{n_j} \lambda_i r_i} \\ p_{DBI,j} = \frac{\sum_{i=1}^{n_{DBI}} \lambda_i r_i}{\sum_{i=1}^{n_j} \lambda_i r_i} \end{cases} \quad (7)$$

where  $p_{BI,j}$  is the probability of important user  $j$  and BESS in the same island;  $p_{DBI,j}$  the probability of DG, important user  $j$  and BESS in the same island;  $n_{BI}$  the set of elements whose fault can cause important user  $j$  and BESS in the same island; and  $n_{DBI}$  the set of elements whose fault can cause DG, important user  $j$  and BESS in the same island.

#### Case 2: DG, BESS and important users are in the same island

The expected output of DG during system failure is:

$$S_{DG} = \frac{1}{T} \sum_{i=1}^T \int_{t=1}^{i+\tau} p_{DG}(t) dt \quad (8)$$

where  $p_{DG}(t)$  is DG output at period  $t$ ;  $\tau$  is the average failure duration when DG, BESS and important users are in the same island which is calculated as

$$\tau = \frac{\sum_{i=1}^{n_{DBI}} \lambda_i r_i}{n_{DBI}} \quad (9)$$

Annual reliability improvement benefit of BESS in Case 2 is expressed as:

$$B_{rel II} = \begin{cases} \sum_{j=1}^I [\min(E_{ENS,j} - S_{DG}, S_{res} - S_{min}) p_{DBI,j} R_{IEA,j}] & \text{if } E_{ENS,j} > S_{DG} \\ 0 & \text{if } E_{ENS,j} \leq S_{DG} \end{cases} \quad (10)$$

In (4)–(9),  $n_j$ ,  $n_{BI}$  and  $n_{DBI}$  can be calculated through Minimal Path Method. The elements include transformers, power lines, circuit breakers and switches, and just individual element failures are considered. Reliability improvement benefit of BESS is expressed as:

$$B_{rel} = B_{rel I} + B_{rel II} \quad (11)$$

This calculation method could be applied to the case in which there are more than one BESS in distribution system. If there are two BESS in an island with important users,  $S_{min}$  and  $S_{res}$  are calculated as (12) and (13).  $n_{BI}$  in (7) represents the set of elements whose fault can cause important user  $j$  and these two BESS in the same island.  $n_{DBI}$  in (7), (8), (10) represents the set of elements whose fault can cause DG, important user  $j$  and two BESS in the same island.

$$S_{min} = \sum_{i=2} S_{oc,min,i} S_{nom,i} \quad (12)$$

$$S_{res} = \sum_{i=2} \left( \sum_{t=1}^T S_{oc,i,t} \frac{S_{nom,i}}{T} \right) \quad (13)$$

## 4 Optimal planning model of BESS

Cost-benefit analysis of BESS in ADS is shown in Fig. 3. Benefits of BESS contain four items and the cost refers to one-time investment cost, operation and maintenance (O&M) cost.

These items include both planning phase and operation phase. Therefore, in order to keep the unity, every item is turned into uniform annual value. The following expressions are transformation coefficients.

$$\begin{aligned} \gamma_{F/A} &= \frac{i_r}{(1 + i_r)^{\tau_{BES}} - 1} \\ \gamma_{P/A} &= \frac{i_r(1 + i_r)^{\tau_{BES}}}{(1 + i_r)^{\tau_{BES}} - 1} \end{aligned} \quad (14)$$

where  $\gamma_{F/A}$  and  $\gamma_{P/A}$  are transformation coefficients of final value and present value to uniform annual value, respectively;  $i_r$  the interest rate; and  $\tau_{BES}$  the service life of BESS.

### 4.1 Direct benefit

Direct benefit refers to the extra income that can be obtained immediately from the operation of BESS, including energy storage arbitrage and loss reduction. For DisCo is the investment subject of BESS in this paper, direct benefit can be calculated by the difference of electricity purchasing cost with and without BESS:

$$B_{dir} = \sum_{t=1}^T c_{grid,t} (p_{gn,t} - p_{gw,t}) \quad (15)$$

where  $c_{grid,t}$  is electricity price of DisCo purchasing from upper grid; and  $p_{gn,t}$ ,  $p_{gw,t}$  the power purchasing from upper system at period  $t$  without and with BESS, respectively.

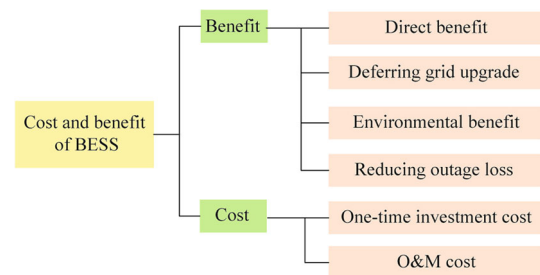


Fig. 3 Cost-benefit analysis of BESS in ADS

## 4.2 Deferring grid upgrade benefit

Electricity generation and consumption no longer need to be balanced in real time because energy storage technology separates them in terms of time and space [8]. Accordingly, deferring grid upgrade benefit of BESS can be realized through peak shaving:

$$B_{\text{del}} = C_e(1 - (1 + i_r)^{-\Delta N_y})\gamma_{P/A} \quad (16)$$

subject to

$$\Delta N_y = \frac{\lg\left(1 + \frac{P_{\text{gn,max}} - P_{\text{gw,max}}}{P_{\text{gn,max}}}\right)}{\lg(1 + \varepsilon)} \quad (17)$$

where  $C_e$  is investment for power network expansion;  $\Delta N_y$  the year numbers of deferring grid upgrade;  $\varepsilon$  annual load growth rate; and  $P_{\text{gn,max}}$ ,  $P_{\text{gw,max}}$  the maximum system loads without and with BESS respectively.

## 4.3 Environmental benefit

Environmental benefit of BESS depends on loss reduction, which means reduction of electricity purchasing from upper grid will lead to the decrease of greenhouse gas emission. Another part is recycling and disposal cost after BESS service life ending, including expenditures for collection and decomposition of waste battery and recovery revenues from metal material extraction [14]. Environmental benefit is expressed in (18)–(19).

$$B_{\text{env}} = B_{\text{emi}} + B_{\text{rec}} \quad (18)$$

subject to

$$\begin{cases} B_{\text{emi}} = \sum_{k=1}^M \left[ \zeta_{\text{grid},k} C_{w,k} \sum_{t=1}^T (p_{\text{gn},t} - p_{\text{gw},t}) \right] \\ B_{\text{rec}} = \left( \sum_{i=1}^m c_{m,i} \rho_{m,i} - c_h \right) \rho_e S_{\text{nom}} \gamma_{F/A} \end{cases} \quad (19)$$

where  $B_{\text{emi}}$  is greenhouse gas emission reduction benefit;  $B_{\text{rec}}$  the battery recycling benefit;  $M$  the set of pollutant types emitting from upper grid;  $m$  the set of metal types contained in batteries;  $\zeta_{\text{grid},k}$  emission density for pollutant  $k$ ;  $c_{w,k}$  penalty cost for upper grid producing unit pollutant  $k$ ;  $c_{m,i}$  recovery price of metal  $i$ ;  $\rho_{m,i}$  content of metal  $i$  in unit-weight battery;  $c_h$  productive expenditure processing unit-weight battery; and  $\rho_e$  energy-weight ratio of BESS.

## 4.4 Life-cycle cost of BESS

Life-cycle cost of BESS is constituted by one-time investment cost and O&M cost. The former is divided into

energy cost and power cost; the latter is mainly related to the rated power of batteries [15].

$$C_{\text{tol}} = (c_s S_{\text{nom}} + c_p P_{\text{nom}}) \gamma_{P/A} + c_p P_{\text{nom}} \beta \quad (20)$$

where  $C_{\text{tol}}$  is life-cycle cost of BESS;  $c_s$  the unit capacity cost of BESS;  $c_p$  the unit power cost of BESS; and  $\beta$  the conversion coefficient of O&M cost converted into the initial power cost.

## 4.5 Optimal planning model of BESS

The objective function of the proposed BESS optimal allocation model is given as:

$$\text{Max } F = B_{\text{dir}} + B_{\text{del}} + B_{\text{env}} + B_{\text{rel}} - C_{\text{tol}} \quad (21)$$

where  $F$  is annual net profit of BESS, which is calculated by direct benefit  $B_{\text{dir}}$ , deferring grid upgrade benefit  $B_{\text{del}}$ , environmental benefit  $B_{\text{env}}$ , reliability improvement benefit  $B_{\text{rel}}$  and life-cycle cost of BESS  $C_{\text{tol}}$ .

The constraints are as follows.

1) Decision variables constraints.

$$C_{p,\min} \leq C_{pl} \leq C_{ph} \leq C_{p,\max} \quad (22)$$

$$S_{oc,\min} \leq S_{od,\min} \leq S_{oc,\max} \quad (23)$$

2) BESS stored energy limits. SOC and power of BESS must satisfy the following constraints.

$$\begin{cases} p_{\text{BES},t}^c \leq P_{\text{nom}} \\ p_{\text{BES},t}^d \leq P_{\text{nom}} \\ p_{\text{BES},t}^c p_{\text{BES},t}^d = 0 \\ S_{od,\min} \leq S_{oc,t} \leq S_{oc,\max} \\ S_{oc,t} = S_{oc,t-1} + \frac{\eta_c \Delta t p_{\text{BES},t}^c - \frac{1}{\eta_d} \Delta t p_{\text{BES},t}^d}{S_{\text{nom}}} \end{cases} \quad (24)$$

where  $\eta_c$  and  $\eta_d$  are charging and discharging efficiency of BESS, respectively; and  $\Delta t$  the duration of time period.

3) Profitability constraint [16]. The configuration schemes are feasible just when the net profit is above 0

$$F > 0 \quad (25)$$

Besides the above three constraints, AC power flow needs to be simulated to calculate  $p_{\text{gn},t}$  and  $p_{\text{gw},t}$  in (15) and (19). Therefore the network constraints should also be considered.

4) System power balance.

$$\sum_{i \in N_{\text{DG}}} P_{\text{DG},i,t} + p_{\text{grid},t} + p_{\text{BES},t}^c - p_{\text{BES},t}^d = \sum_{i \in N} p_{d,i,t} + p_{\text{loss},t} \quad (26)$$





where  $p_{\text{loss},t}$  is network loss at time  $t$ ;  $p_{\text{d.i.t}}$ ,  $p_{\text{DG.i.t}}$ ,  $p_{\text{grid},t}$  are load power, DG output, and power purchasing from upper system at period  $t$ ;  $N$  the number of load nodes; and  $N_{\text{DG}}$  the number of nodes with DGs.

##### 5) Node voltage constraint

$$V_{\min} \leq V_i \leq V_{\max} \quad (27)$$

where  $V_i$  is voltage amplitude of node  $i$ ;  $V_{\min}$  and  $V_{\max}$  are the minimum and maximum limits of voltage with respect to the voltage variation.

##### 6) Line overload constraint. To ensure system safety, the time of feeders overloading should be within the limit, which is expressed as:

$$\frac{T_{\text{overload}}}{T} \leq 0.05 \quad (28)$$

where  $T_{\text{overload}}$  is the time of line overloading.

##### 7) Power interaction limit of distribution system with upper grid.

$$0 \leq p_{\text{grid},t} \leq p_{\text{grid},\max} \quad (29)$$

where  $p_{\text{grid},\max}$  is the upper boundary of power interacted between distribution system and upper grid while 0 is the lower boundary.

## 5 Intelligent single particle optimizer

The proposed optimal configuration model of BESS belongs to a typical nonlinear constrained optimization problem. Furthermore, decision variables of this model are composed by configuration variables including location of BESS, rated capacity  $S_{\text{nom}}$ , rated power  $P_{\text{nom}}$  and operation strategy control variables including  $S_{\text{od},\min}$ ,  $C_{\text{ph}}$  and  $C_{\text{pl}}$ . In order to prevent the interaction between two types of variables and enhance global search ability of traditional particle swarm optimization (PSO), intelligent single particle optimizer (ISPO) is adopted to optimize this model. The solving flowchart is shown in Fig. 4.

In traditional PSO, velocity vector and position vector are updated as a whole particle. Different from that, in ISPO, a particle is divided into several subvectors and velocity vector and position vector are updated based on the subvectors [17]. In this paper, a particle is divided into six subvectors according to decision variables.

In Fig. 4,  $f(\cdot)$  is fitness function.  $z_j^k$  and  $v_j^k$  are position and updating velocity of subvector  $j$  in iteration  $k$ , respectively. The velocity updating formula (marked in (\*\*)) in Fig. 4) is composed of two parts. The first one is diversity part and the second is learning part in which  $a$  is

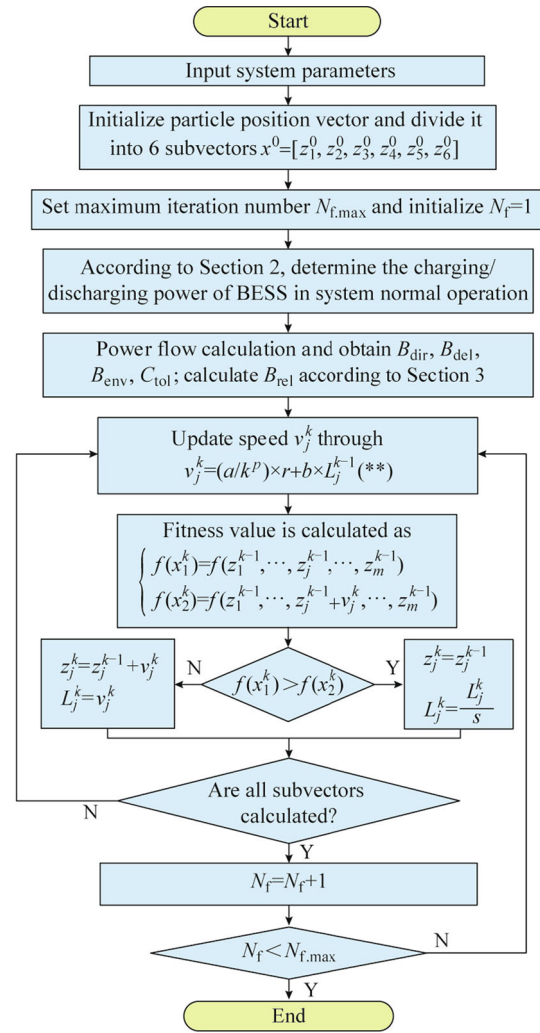


Fig. 4 Flowchart of model solving

diversity factor,  $p$  fall factor,  $s$  shrinkage factor,  $r$  random vector,  $b$  acceleration factor.

In Fig. 4, it can be seen that in the calculation of objective function, system normal operation status and failure status are considered separately. In system normal status, the benefits  $B_{\text{dir}}$ ,  $B_{\text{del}}$ ,  $B_{\text{env}}$  and life-cycle cost of BESS  $C_{\text{tol}}$  are calculated through power flow calculation. In system failure status, reliability improvement benefit of BESS  $B_{\text{rel}}$  is calculated through numerical calculation method proposed in this paper. In practice, there is only one operation line in BESS operation. For a precise calculation, the interaction between these two statuses should be taken into account. The influence of normal status on reliability improvement benefit  $B_{\text{rel}}$  has been considered (through remaining capacity of BESS  $S_{\text{res}}$ ). However, compared to the total time of system normal status, the time span of system failure status is short making the influence of failure status on BESS normal operation relatively small. Thus, to simply the calculation process and

on the premise of no big impact on the results, the influence of system failure on subsequent operation of BESS has been ignored in this paper.

## 6 Case study

### 6.1 Parameters of test system

The proposed method is applied to a modified IEEE 33-node test distribution system illustrated in Fig. 5. As a kind of promising DG, solar photovoltaic (PV) generations are allocated in Node 8, 14, 24, 30. Load data with peak load of  $3.775 + j2.300$  MVA and output of PV are shown in Fig. 6. Important users are set in Node 5, 10, 24, 28. With the advantages of high energy density, high efficiency, environment-friendly and large capacity, sodium-sulfur battery becomes one of the most potential energy storage technologies [18]. Thus, the type of batteries in BESS is chosen as sodium-sulfur battery in this paper. Important parameters are shown in Table 1. Failure rate and repairing time of elements in the system are shown in Table 2. The rest parameters refer to Table A1 and A2.

### 6.2 Optimization results in two configuration mode

In order to compare different configuration mode, two paradigms are discussed in this paper.

Paradigm 1: Centralized configuration mode. There is only one node for BESS allocation. The candidate locations of BSS are Node 2–33.

Paradigm 2: Distributed configuration mode. There are no more than three nodes to install BESS.

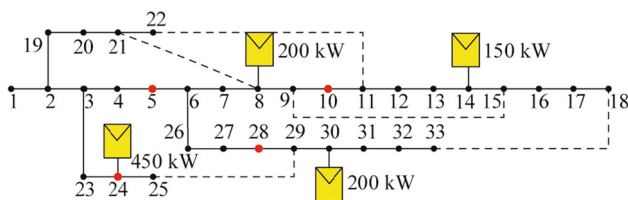


Fig. 5 Modified IEEE 33-node distribution system

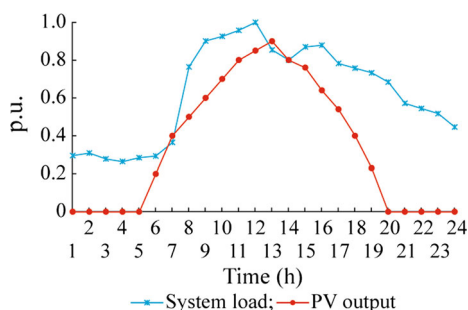


Fig. 6 System load and output of PV

Table 1 Important parameters

Parameter	Quantity	Parameter	Quantity
$C_e$ ( $\times 10^3$ ¥) [8, 9]	1000	$\eta_c$	90 %
$R_{IEA}$ (¥/kWh)	1355	$\eta_d$	90 %
$C_s$ ( $\times 10^3$ ¥/kWh)	1.27	$i_r$	1.5 %
$C_p$ ( $\times 10^3$ ¥/kW)	1.65	$\varepsilon$	1.5 %
$\tau_{BESS}$ (year)	10	$\beta$	0.13
$\rho_e$ (kg/kWh)	3.33	$S_{oc,max}$	0.9
$C_h$ ( $\times 10^3$ ¥/ton)	33.4	$S_{oc,min}$	0.2

Table 2 Failure rate and repairing time of elements

Element	Failure rate	Repairing time
Power line	0.15 times ( $10^2$ km year) $^{-1}$	5 h
Transformer	0.35 times ( $10^2$ units year) $^{-1}$	4 h
Circuit breaker	0.23 times ( $10^2$ units year) $^{-1}$	3 h

Table 3 Optimal decision variables for BESS in two configuration modes

Paradigm	Centralized	Distributed
Node	10	5, 10, 27
$C_{ph}$ (¥)	0.41	0.80
$C_{pl}$ (¥)	0.41	0.39
$S_{od,min}$	0.267	0.306
$P_{nom}$ (kW)	657.8	$287.4 \times 3$
$S_{nom}$ (MVA)	4.789	$1.943 \times 3$

In the process of optimization calculation, the maximum iteration number is 100.  $B = 2$ ,  $s = 4$ ,  $a = p = 1$ . Total simulation time is 365 days (8760 h). Optimization results are shown in Table 3 and Table 4 (in order to reduce the number of variables, the rated power and energy of each candidate node in the distributed configuration mode are set the same, respectively).

As shown in Table 3, no matter which mode of configuration to be adopted, BESS prefers to be allocated near the nodes with important users. This is because the value of  $B_{rel}$  is related with the relative position between important users and BESS in system. The closer the distance between BESS and important users, the greater the probability of both in the same island when system fault occurs, which makes  $B_{rel}$  bigger. Compared with the system load and charging/discharging power of BESS, system loss is rather small. As a result, location of BESS has little effect on the items of  $B_{dir}$ ,  $B_{del}$ ,  $B_{env}$  and  $C_{tol}$  in objective function of the proposed model. In summary, decided by  $B_{rel}$ , BESS is allocated near important users.

In Table 4, compared with centralized configuration mode, due to the bigger BESS rated capacity and rated



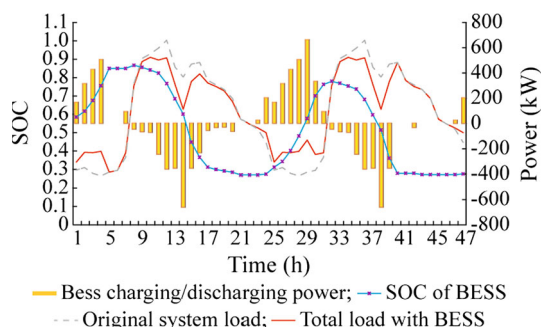
**Table 4** Cost-benefit analysis results of BESS in two configuration modes ( $\times 10^6$  ¥)

Paradigm		Centralized mode	Distributed mode
Node		10	5, 10, 27
Benefits	$B_{dir}$	81.74	97.45
	$B_{del}$	4.26	7.74
	$B_{rel}$	3.06	2.02, 2.45, 1.96
	$B_{env}$	3.34	5.87
Total cost	$C_{tol}$	85.78	$35.58 \times 3$
Net profit	$F$	6.62	10.75
Annual ROI		0.77 %	1.01 %

Note: ROI stands for rate of return on investment which is the ratio of annual profit to total investment

power ( $5.829 \text{ kW} > 4.789 \text{ kW}$ ,  $862.2 \text{ kVA} > 657.8 \text{ kVA}$  in Table 3), total life-cycle cost in distributed mode is greater. This means distributed configuration mode of BESS needs greater capital investment in the early stage. However, distributed mode is still dominant in the aspect of net profit. This is because compared with centralized configuration mode, distributed mode provides more opportunities for BESS to follow important users in system so as to promote reliability improvement benefit. This conclusion can be confirmed in Table 3,  $S_{od,min}$  in distributed mode is bigger than that in centralized mode. Compared to other items, the values of  $B_{rel}$  in both modes are relatively small. This reveals that the system reliability which can be improved by BESS is small.

The optimal charging/discharging power in each time and SOC curve of BESS in centralized configuration mode are shown in Fig. 7 (power greater than 0 represents charging; otherwise, discharging) to observe the performance of the proposed operation strategy. Fig. 7 shows that SOC of BESS is always higher than  $S_{od,min}$  (0.267) which guarantees BESS with enough energy to participate in system fault recovery. Furthermore, from the system load curves with and without BESS, it can be seen that the proposed BESS operation strategy in this paper has the ability of peak load shifting and valley load filling.

**Fig. 7** Optimal charging/discharging power and SOC curve of BESS in centralized mode

### 6.3 Results of different BESS operation strategies

In the proposed optimal planning model, three operation strategy control variables of  $C_{ph}$ ,  $C_{pl}$  and  $S_{od,min}$  can participate in the optimization process of BESS allocation as decision variables. In order to evaluate this feature, optimization results of four different operation strategies in centralized configuration of Node 10 are shown in Fig. 8. These four operation strategies are described as follows.

Strategy 1: the operation strategy proposed in this paper, as shown in Fig. 1.

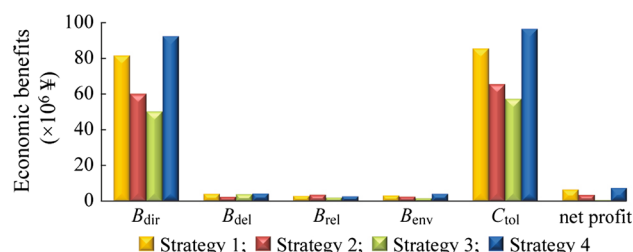
Strategy 2: based on electricity purchasing price: charging during 1:00–6:00, discharging during 11:00–16:00 and floating during the rest time.

Strategy 3: based on system load: charging during 24:00—the next day 7:00, discharging during 9:00–12:00/15:00–16:00/19:00–20:00 and floating during rest time.

Strategy 4: the global optimization strategy.

As shown in Fig. 8, the net profit of Strategy 3 is the lowest, just  $¥ 0.83 \times 10^6$  per year. This is because different from Strategy 2 based on electricity purchasing price, Strategy 3 is based on system load. The variation trends of system load and electricity purchasing price are not consistent (see Fig. 6 and Fig. A1). Therefore, Strategy 3 cannot trace electricity price very well leading to poor economy. Compared to these two fixed strategies (Strategy 2 and Strategy 3), the strategies proposed in this paper can gain more net profit. This verifies the validity of the proposed operation strategy in this paper. Though optimal configuration results of Strategy 1 and Strategy 4 are different, net profits of two strategies are similar. However, calculation time in Strategy 1 is merely 7 % of that in Strategy 4 which can be seen in Table 5. This verifies the feasibility of the proposed operation strategy in this paper.

In all strategies, life-cycle cost of BESS occupies the largest proportion of all items which leading to the low net profit. This phenomenon illustrates that current unit cost of energy storage battery needs to be further reduced.

**Fig. 8** Configuration results of four different BESS operation strategies



**Table 5** Calculation time of four BESS operation strategies

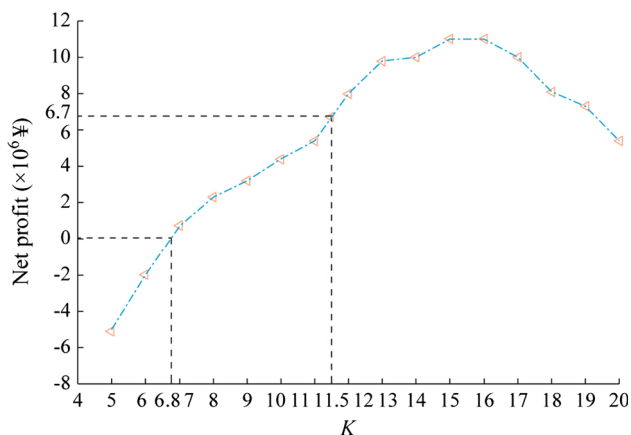
Operation strategy of BESS	Strategy 1	Strategy 2	Strategy 3	Strategy 4
Calculation time (s)	358	178	196	5036

#### 6.4 Results of different electricity price peak-valley difference

Table 4 and Fig. 8 show that the proportion of direct benefit is the largest among all benefit items. The influence of electricity price peak-valley difference on direct benefit is relatively great. In order to further discuss the influence of spot price on net profit, other parameters remain unchanged and the electricity price peak-valley difference increases gradually. The optimal net profits in Node 10 under different electricity price are shown in Fig. 9 in which  $K$  is defined the ratio of the highest price to the lowest price ( $K$  is 11.5 in the original case).

It can be seen from Fig. 9 that just when  $K$  is greater than 6.8, that is, price peak-valley difference greater than ¥ 0.75, net profit is positive and BESS configuration in this system has scale economy. With the increasing of  $K$ , net profit also increases gradually. This is because along with price peak-valley difference increasing, the effect of BESS in peak shifting and valley filling is also improved by setting proper operation strategy so as to increase direct benefit as well as net profit. However, when price peak-valley difference further increases, the effect of BESS on peak shifting and valley filling tends to reach the limit state and the increase in direct benefit is slow, resulting in no increase in net income. When  $K$  is greater than 17, net income begins to reduce quickly. This is because when  $K$  is too large, valley electricity price tends to be zero and cannot be further reduced while peak price can increase unlimitedly, resulting in direct benefit downhill and worsening net income.

From this case, it can be seen that economic benefit of BESS configuration in ADS can be improved by increasing

**Fig. 9** Net profits of BESS configuration in different  $K$ 

the peak-valley difference of electricity price in a certain range but it will decrease when the difference is too high.

## 7 Conclusions

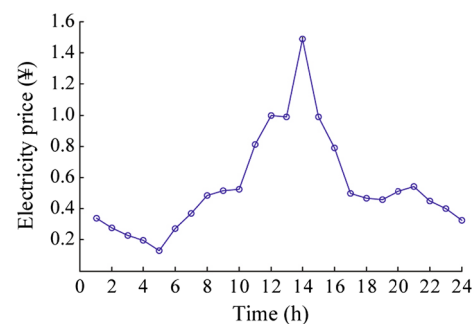
This paper proposes a comprehensive optimal allocation model of BESS considering operation strategy. Furthermore, a numerical calculation method based on expectation for the calculation of system reliability improvement with BESS in planning phase is proposed. The optimal BESS capacity and sizing problem are solved by cost-benefit analysis considering the reliability improvement benefit of BESS. Through the theoretical analysis and simulation results, conclusions can be drawn as follows.

- 1) From the perspective of economic, compared with the centralized configuration mode, distributed mode is preferable for BESS allocated in ADS.
- 2) Compared to the fixed operation strategy. The proposed operation strategy of BESS can obtain more profits with less computation time.
- 3) Economic benefit of BESS configuration in ADS can be improved by increasing the peak-valley difference of electricity price in a certain range but it will decrease when the difference is too high.

Studies in this paper can provide guidance and evaluation for BESS location, sizing selection in ADS and BESS operation strategy also can be determined in the process.

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## Appendix

**Fig. A1** Spot price of DisCo purchasing from upper system

**Table A1** Recyclable materials of sodium-sulfur battery

Type	Contents (t)	Price ( $\times 10^6$ ¥/t)
Na	0.167	20
S	0.214	1.12
Al	0.068	1.58

**Table A2** Externality costs and emission factors

Type	Density (kg/MWh)	Unit penalty Cost (¥/kg)
CO <sub>2</sub>	889	0.210
SO <sub>2</sub>	1.8	14.842
NO <sub>x</sub>	1.6	62.964

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